Remote Laboratories for Education and Research Purposes in Automatic Control Systems

I. Santana, *Student Member, IEEE*, M. Ferre, *Member, IEEE*, E. Izaguirre, R. Aracil, *Member, IEEE*, and L. Hernández

***Abstract*—This paper describes the experiences using remote laboratories for education and research in the field of Control Engineering. The use of remote laboratories for education in subjects of control is increasingly becoming a resorted method by the universities in order to offer a flexible service in schedules with greater and better operation of available resources. Nevertheless, for research activities, remote laboratories are not widely used. The aim of this contribution is thereby to apply the experience of remote laboratories in research applications in order to share complex equipments among different researchers. Some experiments are carried out to demonstrate the effectiveness of using remote laboratories in research experiments related to robotic system. The results of the implementation of remote experimentations to control a 3-DOF parallel robot by using Distance Laboratory System (SLD) are exposed. The performance of the system is evaluated by the possibilities and functionality of the proposed remote laboratory platform.**

***Index Terms*—Remote experiment, remote laboratories, parallel robot, control systems research.**

I. Introduction

EXPERIMENTAL validation represents a fundamental component of education and research methodology in engineering. However, their practical implementations present numerous restrictions due to the cost of equipment, limitations in spatial capacities, security problems, time and maintenance. The use of information technology offers new opportunities in order to reduce these constraints. Remote laboratories can provide remote access to experiments and can allow learners to have access to experiments with less restrictions on time and location, providing the necessary guidance and assuring a safe and secure operation for both the equipment and staff in charge [1].

For engineering distance education courses, remote facilities constitute as the only realistic method of performing many experiments. It must allow remote access to students, no longer constrained by time or geographical considerations, complete laboratory assignments. Thus, it is fair to conclude that remote experimentation facilities enhance the development of skills in the use of real systems and instrumentation [2]. A model for evaluating the effectiveness of remote engineering laboratories and for simulations in education are provided in [3]. The authors concluded that students have learned laboratory content information equally well from both types of laboratories, hands-on and remote labs, and that they have a realistic understanding and appreciation of the practical advantages of remote laboratories.

This paper is focused on the use of remote laboratories for education and research purpose ensuring the security of real equipment. Considering the remote access to real equipment, "Sistema de Laboratorios a Distancia" (SLD) created by the Department of Automatic and Computational Systems of Universidad Central "Marta Abreu" de Las Villas (UCLV) in collaboration with the Universidad Politécnica de Madrid (UPM) has been used. The SLD is a distance laboratory system that allows learning and adjusting predefined controllers, designing new controllers, testing and analyzing the performance of the predefined/designed controllers over a set of physical devices through the Internet [4].

This paper is organized as follows. Section II shows the most relevant works developed for remote laboratories in Control Engineering. Section III describes the characteristics of SLD Web application. The characteristics of remote laboratories for research purpose are shown. Section IV shows the general operation of SLD. Section V describes how access to remote equipment for experimentation. Some topics where SLD could be used are presented. Section VI is focused on the description of the parallel robot used for the research. Section VII presents the results obtained using SLD on research. Section VIII explains the experience and opinions using SLD. Finally, Section IX summarizes the main results of this study.

II. Related Works

There are numerous virtual laboratories and remote experiments available in the literature [5]–[12]. The iLab [13] at Massachusetts Institute of Technology, Cambridge, MA, the LabShare [14] at Curtin University, Australia, and the WebLab-DEUSTO [15] at the University of Deusto, Spain, are important remote laboratories. In [16], the authors provide a literature review of modern remote laboratories. In [17], after a brief overview of state-of-the-art technologies in the development of remote laboratories and presentation of recent and interesting examples of remote laboratories in several areas related to industrial electronics education, some current trends and challenges are also identified and discussed. In addition, in [18], the authors identify possible evolutions for the next generation of remote laboratories that are under a strong current of evolution. Such labs would no longer be restricted to a single topic, where Automatics and Robotics are among the most frequently used tools.

Manuscript received April 14, 2011; revised July 17, 2011, September 20, 2011; accepted November 02, 2011. Date of publication January 26, 2012; date of current version December 19, 2012. Paper no. TII-11-221.

I. Santana, E. Izaguirre, and L. Hernández are with the Automation, Robotic and Perception Research Group, Universidad Central "Marta Abreu" de Las Villas (UCLV), Santa Clara 50100, Cuba (e-mail: ischingx@gmail.com; ching@uclv.edu.cu)

M. Ferre and R. Aracil are with the Centro de Automática y Robótica-CAR UPM-CSIC, Universidad Politécnica de Madrid (UPM), Madrid 28006, Spain (e-mail: m.ferre@upm.es; rafael.aracil@upm.es).

Digital Object Identifier 10.1109/TII.2011.2182518

A variety of different remote experiments and remote laboratories have been developed in the field of Automatics and Robotics control. In [19], an experimental mechatronic system and validation of the control design by remote experiments at Maribor University is presented. A remote laboratory on fuzzy control is presented in [20]. This laboratory offers students and professionals a valuable tool for improving their fuzzy design abilities, and testing the performance of fuzzy controllers in a real DC motor.

A Web-based control laboratory for experimentation on a nonlinear multiple-input-multiple-output (MIMO) system: the three-tank plant, which is introduced in [21]. Using this application, automation technical students can learn many fundamental aspects of control processes in a practical way. A new approach in creating interactive networked control labs is described in [9]. The remote labs created by this approach give students the opportunity to prove the effects of network delays on the controlled system and also to specify their own control algorithm. The Department of Electrical and Computer Engineering at the Utah State University developed a mobile laboratory for Mechatronics and Distributed Control Systems courses [22]. In this low-cost remote laboratory solution, a serial server was connected to the microcontroller of a standalone three-axis robotic wheel assembly.

The Robotics and Automatic Control Telelab (RACT) is a remote laboratory on robotics that was developed at The University of Siena, which extends the field of application of the Automatic Control Telelab (ACT) [23]. This extension consists of adding experiments on a remote robot manipulator. RACT is mainly intended for educational use, and its MATLAB-based architecture allows students to easily put their theoretical knowledge on robotics in practice [24]. The novel Simple Network Robot Protocol (SNRP), which permits the integration of network robots and sensors within an e-learning platform in a simple and reliable manner, is introduced in [6]. The students are able to interact remotely with a real robotic scenario. Networked Control System Laboratory (NCSLab) is a remote laboratory that aims at integrating various devices for experiments located globally and offering various experiment services for users scattered around the world [25]. The system has been used for teaching and research.

García–Zubia and colleagues from the University of Deusto suggests three kinds of laboratories: remote instrumentation, remote parameters control, and remote control logic. In the first kind, the user acts as a mere observer; in the second, the user is able to change some control parameters; and in the third, the client is able to change the inputs, the logic and the parameters of the system [26].

In the greater part of the cited remote control experiments, remote users can run an experiment and adjust the process or the controller parameters from a set of predefined controllers, this includes them in the first two groups defined in [26]. These systems limit the experimentation to some types of controllers (PI, PID, space of state, etc.) they are not suitable for research purposes. Perhaps this explains why remote laboratories have been mainly used for education.

Nowadays, high-performance research rarely takes place in isolated laboratories or as an individual performance. Scientific success is based increasingly on teamwork. Thus, the realization of scientific cooperation and the cooperation in virtual knowledge spaces have crucial relevance [27]. The concept of virtual knowledge spaces has become the importance of academic education. In addition, virtual knowledge spaces are suited intensively as scientific cooperation tool [28]. Remote experimentation using remote laboratories is within this line.

In [29], a remote experimentation system under development for students to conduct a range of experiments in science and engineering education is presented. Moreover, in [30], the authors value the possibilities of remote access for sophisticated equipment located at the factory shopfloor. In [31], the authors present a new generation of pharmacy robots based on micro-servers and Web 2.0 technologies. This new technology offers a faster, more robust, and ecologic service than the classic solutions.

III. Characteristics of the System

SLD is a remote laboratory whose main objective is to allow users to learn how to adjust predefined controllers and to design their own controllers in order to be tested in real devices through the Internet.

A. *Common Characteristics of Remote Laboratories*

SLD has some important features in common with most distance laboratories in operation at present.

Ease of use: Using the SLD, the users should only have some knowledge about robotics and control systems. In this way, users are focused on reinforcing these topics and thereby avoid all implementation and operation problems of devices used in the practices.

Availability: Web-based learning systems should be available 24 hours a day. This implies that the system should have self-protection rules for accomplishing this requirement. All the experiments must be equipped with hardware and software devices to prevent damage to the components and the people working in the laboratory.

Accessibility: Since SLD is configured on a Web-platform, users can access the system from any place in the world. Thus, a computer with internet connection and a browser are needed.

Easy and fast user interface: The user interface is a very important part in the development of a Web-based learning system. The main function of this part is to make the practice order and send it to the Web server. SLD user interface is based on HTML pages that use AJAX and PHP functions; this allows the users to access the system fast, without the need of downloading or installing any additional software.

In [15], experts from different universities have ordered ten characteristics of remote laboratories. The characteristics analyzed are: cross-platform, security, Web browsers, intrusiveness, interaction, installation, devices, bandwidth, audio and video, and power. These characteristics describe remote laboratories for education. However, other features should be added for the purpose of research.

B. *Specific Characteristics of Remote Laboratories for Research Purpose*

The remote laboratories should have additional features to be included in the third group of the classification proposed in [26] and to be used in research.

TABLE I
CHARACTERISTICS OF IMPORTANT REMOTE LABORATORIES/EXPERIMENTS PLATFORM AND SLD

Remote laboratories/ experiments	Client soft technology	Server side technology	Practices processing soft	Kinds of laboratories [26]	Education / Research
WebLab-DEUSTO [15]	AJAX, Flash, Java applets, LabVIEW Remote Panel	Web Services, Python, LabVIEW, Java, .NET, C, C++	Xilinx-VHDL, LabVIEW	Instrumentation, parameters and logic Control	Education
NCSLab [25]	AJAX, Flash	PHP	MATLAB/Simulink	Instrumentation, parameters and logic Control	Education / Research
ACT [23]	HTML, Java Applets	PHP	MATLAB/Simulink	Instrumentation, parameters and logic Control	Education
LabShare Sahara [12]	AJAX, Java Applets	Web Services, Java	Java	Instrumentation and parameters Control	Education
iLab [13]	HTML, ActiveX, Java Applets	Web Services, .NET	LabVIEW	Instrumentation, parameters and logic Control	Education
RECOLAB [11]	HTML	PHP	MATLAB/Simulink	Instrumentation and parameters Control	Education
SLD [32]	AJAX, HTML	Web Services, PHP	MATLAB/Simulink	Instrumentation, parameters and logic Control	Education / Research

Users have to be able to design their own experiments and carry out some tests with different inputs to the system. Considering Control Systems, this is translated in order to be able to carry out tests with different algorithms of control, to change the values and signals in the reference inputs and to operate with complex equipment.

The additional characteristics that remote laboratories should have for research are the following.

Controller development in a remote way: One of the most important features of remote laboratories for research is that it allows the users to design their own controllers. Using the MATLAB/Simulink or LabView environments, which are standard tools in the automatic control field, the users do not need to waste time learning new programming languages for implementing a new controller. Through Simulink or LabView graphic interface, a large number of blocks can be chosen and connected in a very simple way, allowing the users to create analog, digital or hybrid controllers very fast.

Reference change: Remote laboratories for research must allow the experiment's references to change in order to verify the controller performance in the presence of different input signals.

Complex equipment: Remote laboratories for research have to allow operating with complex equipment like robot manipulators, parallel robots, etc.

Advance parameter change: Some advance parameters have to allow changes in a research experiments, such as sample time, solver methods, etc. Researchers are not interested in only adjusting some parameters; they need total access to the hardware and controllers.

Equipment security: Because users can implement their own control algorithms, it is essential to ensure the integrity of the equipment. Generally, security is layered. The devices have their own security, such as mechanical stops, saturations, switches, etc. Besides, it is necessary to include saturation in some critical signals in the block diagram. Finally, before running the practices, the system must check that the developed algorithms will not affect the equipment.

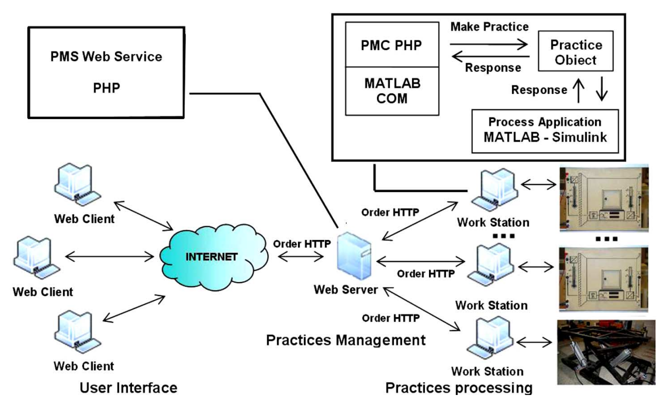

Fig. 1. SLD architecture.

SLD implements these characteristics and makes it possible to be used for research. How these features have been implemented in SLD will be explained with more details in the following sections.

Table I summarizes characteristics of some important remote laboratories/experiments platform and SLD.

IV. GENERAL OPERATION OF THE SLD ARCHITECTURE

SLD is divided into three parts: user interface, practices management and practices processing as shown in Fig. 1. Users interact with the system through the Internet. When accessing the system Web site, users have to first register by giving their username and password and then choose the practice they want to realize. The user can then fill out the form about the practice in a correct way and finally select whether to carry out the practice in a simulated or in a real device.

The Web Service Practice Management Server (PMS) receives data of the practices that users execute. It organizes them by the order of arrival and verifies which workstation can perform the practice in order to send it to the Web Services Practice Management Client (PMC) located in the available workstation. If there is more than one workstation than can

TABLE II
TOPICS WHERE THE SLD COULD BE EFFECTIVELY USED

Subjects	Topics
Modeling and simulation	Experimental Identification of SISO Systems. Transient Response Analysis.
Classic Control	Control System Design by Transient-Response. Control System Design by Frequency-Response. Tuning of PID Controller.
Modern Control	Design of Control System in State Space. Design of Regulator-Type by Pole Placement. Design of State Observer. Optimal Control. Adaptive Control. Intelligent Control. Sliding Mode Controller.
Digital Control	Sample Time Selection. Selection and Tuning of Digital Controller. Digital Leg Compensation. Digital Lag Compensation.
Robotic	Dynamic Modeling of Manipulators. Trajectory Planning. Independent Joint Control. Computer Torque Feed forward Control. Control with Compensation. Adaptive Control.

execute the practice, that supposes equal physical devices have been connected to different workstations, the system chooses which workstation will carry out the execution in the following form.

1) If there are free stations, the system randomly chooses one.
2) If all the stations are busy, the system creates a queue of attention for each one of them.

Importantly, the queue is formed by station, not by practice, which means that there can be different practices for execution. The state of the stations (waiting, busy and off) is kept updated in the database.

The waiting time for each user depends on the execution time of each practice and the number of stations that can be executed. The approximate time of delay is shown in the Web page of each practice. If the time of delay is high, SLD suggests the user to carry out the experiment at another time. If the waiting time is over 6 min, the practice is disabled until it releases the queue.

When the order arrives at the PMC, the data are processed and the practice is carried out using MATLAB and Simulink together with Real Time Workshop (RTW) Toolbox. The direct execution of Simulink scheme represents an advantage since the time and complexity in creating new algorithms of control are drastically reduced. Furthermore, it allows creating and modifying control schemes more easily.

Once the practice has been processed, the feedback is obtained by a Web page showing the processing data. Throughout the practice, a video with the real process is shown to the users [32].

The workstation and the Web Server can be separated through WLAN or Internet. The communications port used is a standard HTTP 80 port, rather than nonstandard TCP/IP random ports, that can be blocked by firewalls.

The system allows two types of practices: one with a predefined controller and another with a controller created by the user.

V. ACCESS TO REMOTE EQUIPMENT FOR EXPERIMENTATION

Table II summarizes some topics, in Automatic Control Systems, where the SLD could be effectively used. Modern Control, Digital Control, and Robotics are subjects fundamentally taught in postgraduate courses and for research works.

SLD has been used in teaching activities as well as undergraduate and postgraduate courses at UCLV [33], at UPM [32], [34] and other countries like Mexico, Brazil, and Venezuela. At present, the experiences developed use a DC motor and a robot manipulator at UCLV and a DC motor and thermal system at UPM. A parallel robot has recently been included at UCLV.

A. *Practices With Predefined Controller*

In the exercises with predefined controller, users only need a Web browser to access SLD Websites. The user will be able to change the value of certain parameters of interest by evaluating the effects that arise in the response of the system. Considering these schemes, it is possible to approach subjects of: experimental identification of SISO systems, dynamic analysis of systems, analysis and design in the field of the time, effects of the control actions, and adjustment of controllers with SISO and MIMO systems.

The exercises with predefined controller are very useful for education because they focus the student learning on the fundamental aspects of the theory that the professor wants to emphasize.

The laboratory of practices of the UPM is formed by eight positions, each equipped with a computer, a data acquisition card (AD622 of Humusoft) and two scale models, a thermal system and DC motors. A DC motor and the thermal system are single input and single output processes (SISO) that allow carrying out experiments related with identification, position control, velocity control and temperature control, without load disturbances.

For example, a practice for testing PID controller performance in a thermal scale model is described next.

The theoretical transfer function of the thermal system shows in (1)

$$G(s) = \frac{0.9}{(1+7s)^3}. \tag{1}$$

A Web page of the practice is shown in Fig. 2.

In these practices, students have several possibilities in testing the effects of proportional (kp), integral (ki), and derivative (kd) control actions on the system step transient-response: first, by simulations and, second, in a real way.

The PID controller could be adjusted by Ziegler–Nichols method for example. Fig. 3 shows the steady-state response of a real system to changes in the input from 0 to 5 step function. Fig. 3(a) and (b) show the effects of gain change on the transient-response and the steady-state error, respectively. Fig. 3(c), with I control action, shows how the steady-state error goes to 0, but the system response is slow; in Fig. 3(d), the system becomes faster as consequences of action D.

In parametric practices, the safety of the equipment at SLD level is guaranteed by limiting the value of the parameters. In this case, the value of the controller's parameters kp, ki, and kd

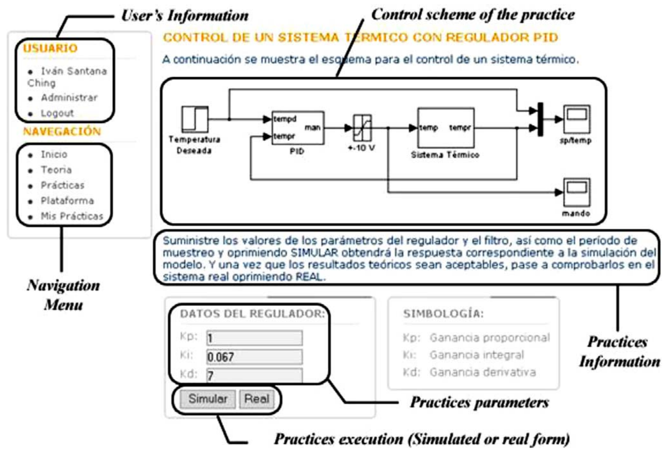

Fig. 2. PID controller Web page for thermal system.

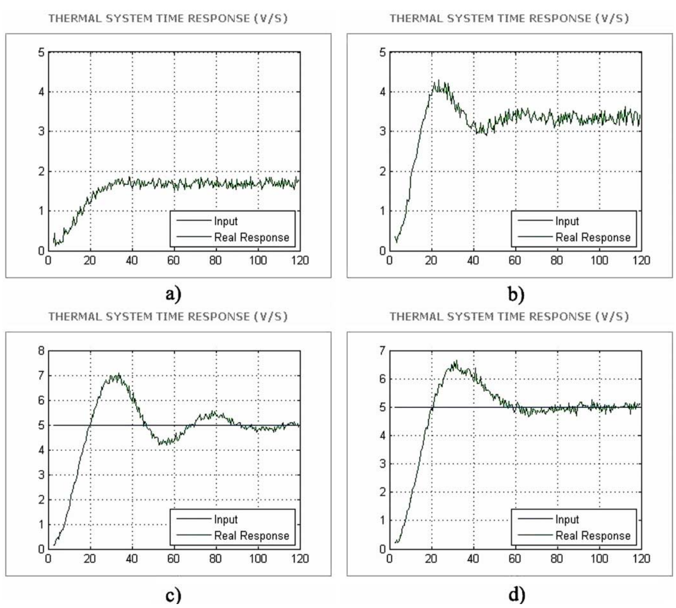

Fig. 3. Example time response of a real system. (a) P controller $\mathrm{Kp} = 0.5$. (b) P controller $\mathrm{Kp} = 2$. (c) PI controller $\mathrm{Kp} = 2$ and $\mathrm{Ki} = 0.15$. (d) PID controller $\mathrm{Kp} = 2$, $\mathrm{Ki} = 0.15$ and $\mathrm{Kd} = 7$.

will be adjusted between 0 to 10, otherwise, an error is generated by the system. In addition, the thermal system has voltage limiters for protection. In the Simulink model, the saturation blocks are placed, as shown in Fig. 2. This type of practices has been used at UPM in subjects of Automatic Control Systems [32]–[34].

B. Practices With Controller Created by the User

The practices with the user-defined controller have great potentials in education, but the greater advantage could be obtained in research. They allow making experimentation of different control methods, classic and modern. The response of the system can be analyzed with different reference and disturbance signals and changing the sample time.

Working with these types of practices, users need to have MATLAB and Simulink software installed in order to modify the downloaded Simulink file. When a practice with the user-defined controller is selected, a Web page is displayed. In

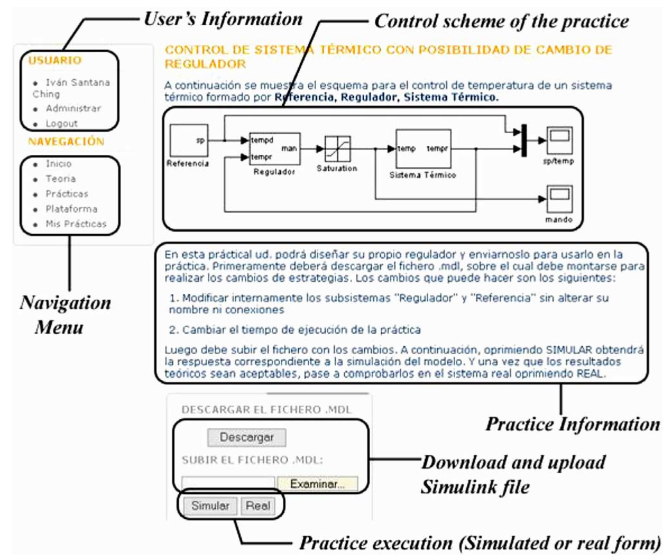

Fig. 4. Defined user controller Web page for thermal system.

Fig. 4, the Web page of practice with user-defined controller for thermal system is shown.

The Web page allows downloading a Simulink file, which contains the block diagram of the practice. In addition, the user can modify the subsystems Reference and Regulator using MATLAB and Simulink software. However, they cannot modify the name or the amount of inputs and outputs of the subsystems. Users can also change the sample time, execution time, and other important parameters.

The safety of the equipment in this type of practices at SLD level is guaranteed by running the model on Simulink in *Normal* simulation mode before the execution on the real device. This simulation allows the calculations of certain critical parameters of the system and the comparison with limited values that assure that the real equipment will not be damaged during the execution of the experiment. Each physical system has its own critical parameters to oversee. Moreover, saturation and filtered blocks are added in order to limit the excessive amplitude of command signals and some critical signals.

This type of practice could be used in any kind of device, but more interestingly in complex systems like robots. The robot manipulator and a parallel robot are systems with MIMO characterized by dynamic interactions and nonlinear behavior. They allow implementing more complex positioning and trajectory tracking control schemes.

With this work, the authors try to take a step forward in the application of the remote laboratories. The main objective of this work is to develop training and carry out better experiments about complex devices with possibilities of changing the control algorithms.

VI. Parallel Robot Used for Research Purposes

Parallel robots have received special attention from the systems and control community based on their high force-to-weight ratio and widespread applications [35], [36]. Several research papers have been published, prototypes have been built, new

Fig. 5. SIMPRO 3DOF pneumatic driver simulator parallel platform.

topologies invented, and consequently their applications are increasing [37]–[39]. The field of parallel robots is highly multidisciplinary and the process of building successful architectures requires expertise in mathematics, kinematics, dynamics [40], [41], and in many other fields in addition to the application-related know-how [42], [43].

The robotic system used for remote experimentations on research is a 3-DOF parallel manipulator controlled by pneumatic actuators (Fig. 5). The parallel robot is produced by SIMPRO for driving simulator purpose. The parallel robot model is described in [44].

Inverse kinematics expressions of the 3-DOF parallel mechanism used in the remote experiments are development in [44], including the design of position controllers and dynamic identification of electro-pneumatic systems. The design of the position controller was performed via pole placement, where the closed loop performance is dominated by complex conjugate pair of poles with $\zeta = 0.7$ and $\omega_{\rm n} = 10$ rad/s. Dynamic online identification was performed by using a pseudo random binary signal (PRBS) in order to obtain the adequate excitation of system in the closed-loop configuration with variable proportional gain. The corresponding transfer function of designed controllers $(U(s)/E(s))$ and servo-pneumatic systems $(Y(s)/U(s))$ are as follows.

Controller for actuator 1

$$\frac{U_1(s)}{E_1(s)} = \frac{265(s^2+7.726s+253)(s+3.03)}{s(s^2+146.7s+6267)}. \tag{2}$$

Controllers for actuators 2 and 3

$$\frac{U_2(s)}{E_2(s)} = \frac{U_3(s)}{E_3(s)} = \frac{32(s^2+7.726s+1349)(s+3.03)}{s(s^2+146.7s+6267)}. \tag{3}$$

Piston 1

$$\frac{Y_1(s)}{U_1(s)} = \frac{245.94}{s(s^2+7.726s+253)} \tag{4}$$

Piston 2 and 3

$$\frac{Y_2}{U_2} = \frac{Y_3}{U_3} = \frac{2008.3}{s(s^2+7.276s+1349)} \tag{5}$$

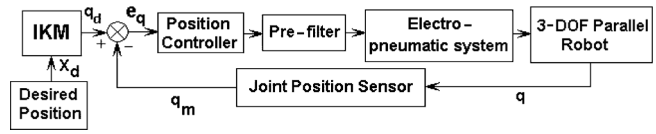

Fig. 6. Block diagram of joint-space position control.

where

$$\begin{aligned}
\mathrm{U(s)} &= \text{controller command signals}\\
\mathrm{E(s)} &= \text{error}\\
\mathrm{Y(s)} &= \text{joint's position.}
\end{aligned}$$

A. Decoupled Control Scheme

An independent joint position control is proposed. In the design, it has been considered that the control system must respond with sufficient robustness against dynamic disturbances [45].

Each leg is actuated by pneumatic cylinder FESTO DNC-125-500 governed by a MPYE-5-3/8 proportional flow valve, the joint's displacements are measured by MLO-POT-500 linear potentiometers with $+-0;01$ mm of accuracy.

The control scheme of a single actuator is represented in Fig. 6. This block diagram does not use the inverse dynamics model of the plant avoiding the calculation of the inverse dynamics of the robot [38]. On the other hand, the use of inverse kinematics allows knowing the individual value of the elongations of the pistons as function of the pose of the moving platform. The measurement signals coming from the high precision linear potentiometers are processed by a Humusoft MF624 board (16 I/O), which is mounted on a commercial PC (Pentium D 3 GHz processor, 256 Mb RAM). The analog command signal is sent to the proportional flow valve, which feeds the pneumatic cylinder.

The control algorithm is executed in real time environment with 10 ms of sampling time in the real-time Windows Target of MATLAB.

The controller has to be placed in the cascade with a Butterworth filter of 80 Hz of cut frequency, to guarantee that the valve is not excited above its bandwidth. That way, controllers satisfy all the formulated demands in the control problem.

VII. SLD for Researchers

In this section, the performance of the decoupled position control scheme of industrial 3-DOF pneumatic parallel platform is evaluated by means of remote experimentation. The SLD Web platform is used for carrying out the corresponding remote experiments by applying time-varying desired path in orientation angles and elevation to be followed by the mobile platform. The experiment would be performed by different types of controllers created by the user.

A. Remote Experimental Design

As mentioned, the designed remote experiment allows verifying the control system's performance based on different control strategies. Moreover, it also permits analyzing the time re-

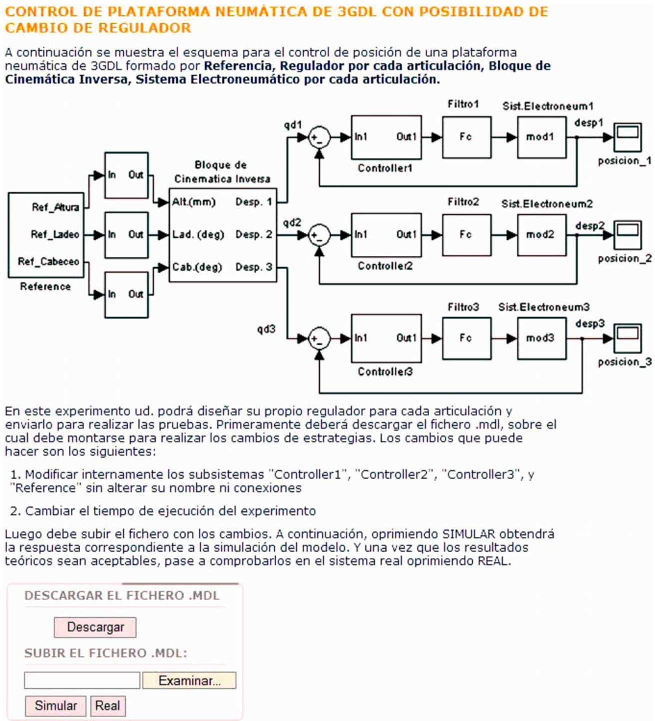

Fig. 7. Control parallel robot Web page.

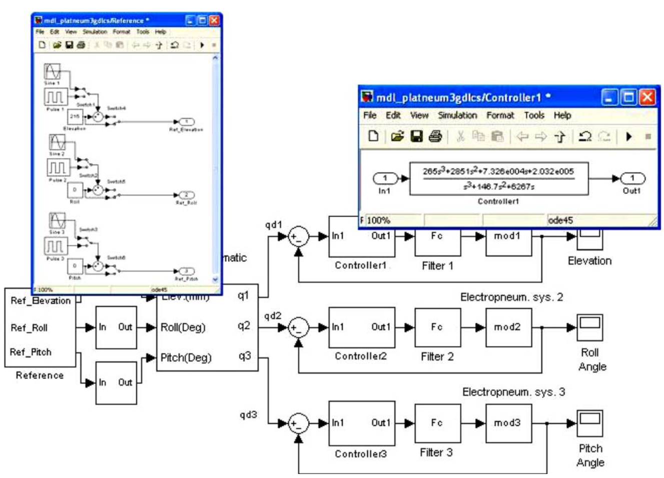

Fig. 8. Simulink block diagram of the experiment.

sponse characteristics of the closed loop system with different reference input signals.

For the remote experiment, an appropriate Webpage was constructed (Fig. 7). The Webpage allows downloading a Simulink file with the block diagram of the proposed controlled system. The Simulink-model contains all the simulations parameters necessary to perform the remote experiment, including control strategy and test input signals (Fig. 8).

The users can freely modify the reference input signals in the subsystems and controller1, controller2, controller3 for each electro-pneumatic actuator by means of MATLAB and Simulink package software. However, they cannot modify the name or the number of input/output ports of the subsystems. In addition, users can change the sample time, execution time and others important simulation parameters.

When the Simulink model is finished and saved, the user can upload the block diagram (.mdl file) to the SLD—which is running on the workstation (Fig. 1)—in order to perform the corresponding experiments. As mentioned, before carrying out the practices in the real device, SLD makes an execution of the Simulink model in *Normal* simulation mode as well as several tests that, in parallel robots, are focused on the following objectives.

1) To verify that the Cartesian trajectories do not surpass the parallel robot workspace.
2) To check that the robot's joints do not exceed the mechanical limits according to the restrictions of the mechanism.
3) To avoid, through a signal frequency analysis, that the robotic system presents high-frequency oscillations, this can mechanically disarrange the robot and/or damage its actuators.

Once these aspects have been determined, the SLD implements the controller, compiles the system using the RTW Toolbox and carries out the experiment in real time. In case the SLD detects that the designed controller represents a risk for the parallel robot, the system will not allow the execution of the real experiment. The user is informed of the cause and is given the simulation graphs and performance data in order to evaluate the system performance.

Additional experiments can be developed considering changes in the reference signals, controller settings, and control methods; furthermore, other blocks could also be available for modification, enhancing the possibilities of research. The architecture of the closed loop control system can be designed in state-space or transfer function representation, and indistinctly in analog or digital version.

B. Remote Experimental Results

For an experimental test, the dynamic model of servo systems—defined by (4) and (5) are used- and the transfer functions of controllers are according to (2) and (3).

To evaluate the performance indexes of the robotic closed-loop system in terms of joint's displacements and positioning errors, four different experimental tests were developed with several time-varying trajectories given in Cartesian space that are shown in Table III.

Test 4 was executed with sinusoidal input signals with constant frequency of 0.84 rad/s, starting from the initial elevation of mobile platform of 1285 mm in which assuring the 50% of elongation of pneumatic actuators. A low-pass second-order filter with cutoff frequency of 80 Hz is inserted in the forward path to limit the excessive amplitude of command signal over the flow proportional valves bandwidth.

Because robotic control commands are executed in the joint space, while robotic motions are specified in the task space, it is strongly necessary to include the inverse kinematics relations in the control scheme in order to find the corresponding sets of joint displacements given the desired position and orientation of the end-effector. So, the outputs of IK block are the desired joint's coordinates, which are used to generate the joint position errors.

During experiments, the joint coordinates are measured and compared with the reference signals. The obtained results of

TABLE III
INPUT SIGNALS APPLIED TO THE MOBILE PLATFORM DURING EXPERIMENTS

Number of Experiments	Desired Command Signals		
	Height	Roll angle (deg)	Pitch angle (deg)
Test 1	Pulse train of 100 mm of amplitude and 12 seconds of period	0 deg	0 deg
Test 2	215 mm (constant)	Pulse train of 15 deg of amplitude and 6 seconds of period	0 deg
Test 3	215 mm (constant)	0 deg	Pulse train of 8 deg of amplitude and 6 seconds of period
Test 4	Sinusoidal signal with ± 100 mm of amplitude and constant frequency	Sinusoidal signal with ± 6 deg of amplitude and constant frequency	Sinusoidal signal with ± 5 deg of amplitude and constant frequency

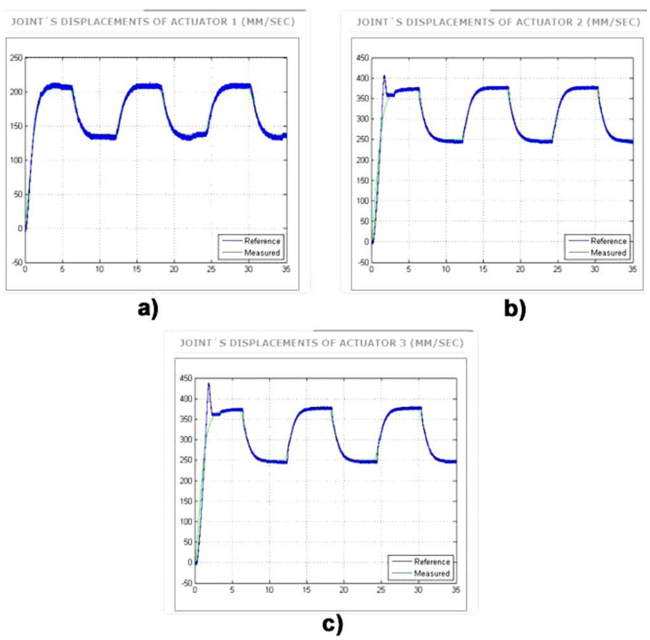

Fig. 9. Measured and reference displacements (mm) of active joints during the first experiment. (a) Actuator 1. (b) Actuator 2. (c) Actuator 3.

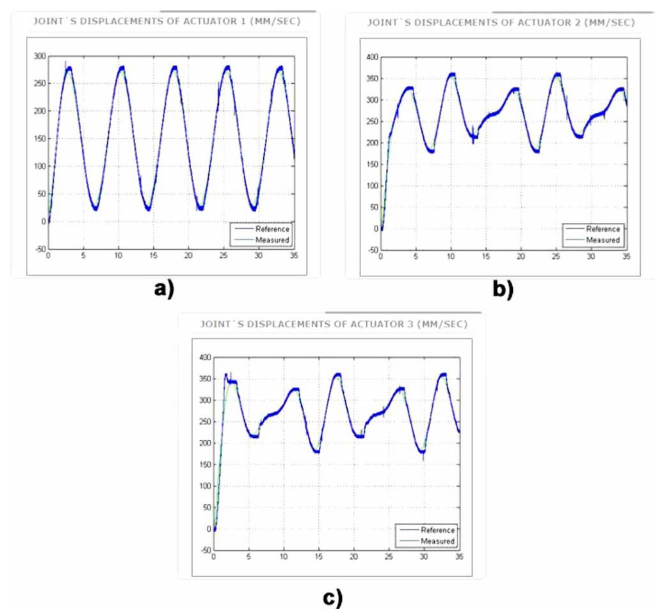

Fig. 10. Time history of joint trajectories obtained from fourth experiment, considering sinusoidal elevation and orientation of moving platform. (b) Actuator 2. (c) Actuator 3.

first and fourth remote experiments are shown in Figs. 9 and 10, respectively.

VIII. RESULTS USING SLD FOR EDUCATION AND RESEARCH

SLD has been used at UCLV and UPM in activities of teaching as well as undergraduate and postgraduate course. In 2007, the SLD platform received an Award from the Academy of Sciences of Cuba for its development and use.

There is a close relationship between the complexity of real equipment and its purpose. The methodology applied is that less complex equipment such as DC motors and thermal systems, are used in courses for undergraduate and master. While more complex equipment such as robots, are used by Ph.D. students and researchers to test novel control algorithms.

According to our experience, the best methodology for SLD in education consists of combining hands-on and remote works taking advantage of both scenarios. Present works have a great formative value for the students. It allows them to know and manipulate real equipment, and to perform all connections and auxiliary jobs required before being used. Once students are familiarized with the systems, they can perform the works remotely in order to save time and focus on data acquisition and interpretation. The effective time using the devices remotely is strongly reduced, because programming and capturing of data require 10–20 min. The accomplishment of remote works is the time saved by students and the shared use of resources. This is particularly important when the number of students is large and the equipment is expensive. Another interesting aspect that arises when combining hands-on and remote practices is the unlimited time for using equipments. The students can use them until they consider that the aimed objectives have been reached [32]–[34].

The results obtained at the last courses using SLD were positive. Students were very motivated with SLD use for the remote practices. Several studies have been done to evaluate the impact in the teaching of control engineering using the methodology that combines hands-on and remote laboratories. Among the techniques used include expert groups, the participant's observation during the execution of laboratory practices and surveys.

Survey results, in a scale from 1 to 5 (completely disagree to completely agree), behaved as follows (Table IV). A sample of 170 students from two last courses was chosen.

Many researchers and Ph.D. students have contributed various excellent control algorithms to experiment devices in SLD, especially with parallel robot and the robot manipulator. The opinion is very good and would extend the experience even

TABLE IV
SURVEY RESULTS

Items	Average	Median	Standard deviation
The real practices in the laboratory were very important for my formation	4,23	4	0,68
The amount of real practices in the laboratory was acceptable	3,90	4	0,77
Hands-on practices have been useful for my learning	3,84	4	0,94
Remote practices have been useful for my learning	3,60	4	1,05
The combination of hands-on with remote activities have verified my skills and my knowledge	3,74	4	0,91
How do you rate the performance of the SLD as a tool for remote access to real physical devices?	4,15	4	0,84
How do you value remote practices developed through SLD?	3,64	4	0,79
I would recommend SLD to other students	4.02	4	1.00

more. This will enable the collaboration among universities and between universities and companies.

IX. CONCLUSION

SLD has proven to be a powerful tool for managing the remote laboratory, as well as in education and research.

Using remote experimentation, the cost required for doing research on parallel robots can be reduced. It is mainly due to a great number of researchers from all parts of the world being able to access the remote laboratory. Effective collaboration and communication among researches can be done; the results of different experiments are stored in memory for subsequent studies. In addition, a large number of remote experiments can be carried out by researchers located in others universities in order to evaluate the dynamic performance of the robotic system. Important research can be conducted like system dynamic identification, dynamic parameters evaluations, robust tracking performance, etc.

The principal benefit of using remote laboratories for research is to share expensive resources among universities, industry, and research centers, which allows the distribution of cost. Another important advantage is the creation of a workbench that will be accessible to several researchers in order to develop and test advanced algorithms of control.

The remote experimental results confirm the expected performance of the system in the joint space control scheme. As future works, control strategies for the parallel robot can be improved with a cascaded control loop in order to better the overall performance of the control system, in path tracking, motion simulator application, etc.

REFERENCES

[1] J. J. Rodriguez-Andina, L. Gomes, and S. Bogosyan, "Current trends in industrial electronics education," *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3245–3252, Oct. 2010.

[2] M. Callaghan, J. Harkin, T. McGinnity, and L. Maguire, "Intelligent user support in autonomous remote experimentation environments," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2355–2367, Jun. 2008.

[3] J. V. Nickerson, J. E. Corter, S. K. Esche, and C. Chassapis, "A model for evaluating the effectiveness of remote engineering laboratories and simulations in education," *Comput. Education*, vol. 49, pp. 708–725, 2007.

[4] A. Sartorius *et al.*, "Platform for distance development of complex automatic control strategies using Matlab," *Int. J. Eng. Education (IJEE), Special Issue on Matlab and Simulink in Engineering Education*, vol. 21, pp. 790–797, 2005.

[5] A. Leva and F. Donida, "Multifunctional remote laboratory for education in automatic control: The CrAutoLab experiences," *IEEE Trans. Ind. Electron.*, vol. 55, no. 6, pp. 2376–2385, Jun. 2008.

[6] R. Marin *et al.*, "Remote programming of network robots within the UJI industrial robotics telelaboratory: FPGA vision and SNRP network protocol," *IEEE Trans. Ind. Electron.*, vol. 56, no. 12, pp. 4806–4816, Dec. 2009.

[7] A. Balestrino, A. Caiti, and E. Crisostomi, "From remote experiments to web-based learning objects: An advanced telelaboratory for robotics and control systems," *IEEE Trans. Ind. Electron.*, vol. 56, no. 12, pp. 4817–4825, Dec. 2009.

[8] L. M. Jimenez *et al.*, "Remote control laboratory using Matlab and Simulink," in *Proc. IEEE Int. Symp. Ind., ISIE'07*, 2007, pp. 2963–2967.

[9] G. Farias, R. De Keyser, S. Dormido, and F. Esquembre, "Developing networked control labs: A Matlab and easy java simulations approach," *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3266–3275, Oct. 2010.

[10] M. Stefanovic, M. Matijevic, and V. Cvijetkovic, "Web-based laboratories for distance learning," *Int. J. Eng. Education*, vol. 25, pp. 1005–1012, 2009.

[11] R. Puerto *et al.*, "RECOLAB: Laboratorio remoto de control utilizando Matlab y Simulink," *Revista Iberoamericana de Automática e Informática Industrial*, vol. 2, pp. 64–72, 2005.

[12] D. Lowe, S. Murray, L. Weber, and M. D. L. Villefromoy, "LabShare: Towards a national approach to laboratory sharing," in *Proc. 20th Australasian Assoc. Eng. Edu. Conf., AAEE'09*, Univ. Adelaide, Adelaide, Australia, 2009, pp. 458–463.

[13] V. J. Harward *et al.*, "The iLab shared architecture: A web services infrastructure to build communities of internet accessible laboratories," *Proc. IEEE*, vol. 96, pp. 931–950, 2008.

[14] F. Anwar, E. Lindsay, and R. Sarukkalige, "Key factors for determining the suitability of converting a fluid-mechanics laboratory to remote-access mode," *Australasian J. Eng. Edu.*, vol. 17, pp. 11–18, 2011.

[15] J. Garcia-Zubia, P. Orduna, D. Lopez-de-Ipina, and G. R. Alves, "Addressing software impact in the design of remote laboratories," *IEEE Trans. Ind. Electron.*, vol. 56, no. 12, pp. 4757–4767, Dec. 2009.

[16] J. Ma and J. V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review," *ACM Comput. Surv.*, vol. 38, p. 7, 2006.

[17] L. Gomes and S. Bogosyan, "Current trends in remote laboratories," *IEEE Trans. Ind. Electron.*, vol. 56, no. 12, pp. 4744–4756, Dec. 2009.

[18] C. Gravier *et al.*, "State of the art about remote laboratories paradigms—Foundations of ongoing mutations," *Int. J. Online Eng. (iJOE)*, vol. 4, pp. 19–24, 2008.

[19] A. Rojko, D. Hercog, and K. Jezernik, "Power engineering and motion control web laboratory: Design, implementation, and evaluation of mechatronics course," *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3343–3354, Oct. 2010.

[20] M. Valles, J. L. Diez, J. L. Navarro, and A. Valera, "Remote access to MATLAB-based Laboratories: Application to the fuzzy control of a DC motor," *Int. J. Eng. Edu.*, vol. 26, pp. 1343–1353, 2010.

[21] R. Dormido *et al.*, "Development of a web-based control laboratory for automation technicians: The three-tank system," *IEEE Trans. Edu.*, vol. 51, pp. 35–44, 2008.

[22] B. Ramaswamy, Y. Chen, and K. L. Moore, "Omni-directional robotic wheel-mobile real-time control systems laboratory," *Int. J. Eng. Edu.*, vol. 24, pp. 92–100, 2008.

[23] M. Casini, D. Prattichizzo, and A. Vicino, "The automatic control telelab: A web-based technology for distance learning," *IEEE Control Syst. Mag.*, vol. 24, pp. 36–44, 2004.

[24] M. Casini, F. Chinello, D. Prattichizzo, and A. Vicino, "RACT: A remote lab for robotics experiments," in *Proc. 17th World Congr. Int. Fed. Autom. Control (IFAC)*, Seoul, Korea, 2008, pp. 8153–8158.

[25] Y. Qiao, G.-P. Liu, G. Zheng, and W. Hu, "NCSLab: A web-based global-scale control laboratory with rich interactive features," *IEEE Trans. Ind. Electron.*, vol. 57, no. 10, pp. 3253–3265, Oct. 2010.

[26] J. García-Zubia *et al.*, "An approach for weblabs analysis," *Int. J. Online Eng. (iJOE)*, vol. 3, 2007.

[27] S. Oncu and H. Cakir, "Research in online learning environments: Priorities and methodologies," *Comput. Edu.*, vol. 57, pp. 1098–1108, 2011.

[28] S. Jeschke *et al.*, "Networked virtual and remote laboratories for research collaboration in natural sciences and engineering," in *Proc. 2nd Int. Conf. Adaptive Sci. Technol.*, 2009, pp. 73–77.

[29] C. Colwell, E. Scanlon, and M. Cooper, "Using remote laboratories to extend access to science and engineering," *Comput. Edu.*, vol. 38, pp. 65–76, 2002.

[30] M. Cooper and J. M. M. Ferreira, "Remote laboratories extending access to science and engineering curricular," *IEEE Trans. Learning Technol.*, vol. 2, pp. 342–353, 2009.

[31] J. Garcia-Zubia, I. Trueba, and D. Lopez-de-Ipina, "WEB 2.0 pharmacy robots," in *Proc. 7th Int. Conf. Remote Eng. Virtual Instrumentation*, Stockholm, Sweden, 2010, pp. 12–18, KTH.

[32] I. Santana *et al.*, "Aplicación del sistema de laboratorios a distancia en asignaturas de regulación automática.," *Revista Iberoamericana de Informática Industrial (RIAII)*, vol. 7, pp. 46–53, 2010.

[33] I. Santana *et al.*, "Design of servo system in state space using distance laboratory system (DLS)," in *Proc. Int. Conf. Comput. Supported Edu. (CSEDU 2009)*, Lisboa, Portugal, 2009, pp. 296–300.

[34] I. Santana *et al.*, "Distance practices in subjects of automatic control," in *Proc. IEEE Eng. Edu.—The Future of Global Learning in Engineering Education (EDUCON)*, Madrid, 2010, pp. 967–972.

[35] J. P. Merlet*, Parallel Robots*, 2nd ed. New York: Springer, 2006.

[36] H. Abdellatif and B. Heimann, "New experimental results on the compensation of static friction in passive joints of robotic," *IEEE Trans. Control Syst. Technol.*, vol. 18, pp. 1005–1010, 2010.

[37] M. Jin, J. Lee, P. H. Chang, and C. Choi, "Practical nonsingular terminal sliding-mode control of robot manipulators for high-accuracy tracking cont.," *IEEE Trans. Ind. Electron.*, vol. 56, pp. 3593–3601, 2009.

[38] F. Pierrot *et al.*, "Optimal design of a 4-DOF parallel manipulator: From academia to industry," *Robotics, IEEE Transactions on*, vol. 25, pp. 213–224, 2009.

[39] X. Zhu, G. Tao, B. Yao, and J. Cao, "Integrated direct/indirect adaptive robust posture trajectory tracking control of a parallel manipulator driven by pneumatic muscles," *Control Systems Technology, IEEE Transactions on*, vol. 17, pp. 576–588, 2009.

[40] Q. Xu and Y. Li, "Dynamic modeling and robust control of a 3-PRC translational parallel kinematic machine," *Robotics and Computer-Integrated Manufacturing*, vol. 25, pp. 630–640, 2009.

[41] L. Wang, T. Chai, and L. Zhai, "Neural-network-based terminal sliding-mode control of robotic manipulators including actuator dynam," *IEEE Trans. Ind. Electron.*, vol. 56, pp. 3296–3304, 2009.

[42] H. Liu, T. Huang, and D. G. Chetwynd, "A method to formulate a dimensionally homogeneous jacobian of parallel manipulators," *IEEE Trans. Robot.*, vol. 27, pp. 150–156, 2011.

[43] A. Muller, "Consequences of geometric imperfections for the control of redundantly actuated parallel," *IEEE Trans. Robot.*, vol. 26, pp. 21–31, 2010.

[44] L. Hernández *et al.*, , G. R. Naik, Ed., "Kinematic task space control scheme for 3DOF pneumatic parallel robot," in *Intelligent Mechatronics*. Rijeka, Croatia: InTech, 2011, pp. 67–84.

[45] E. Izaguirre *et al.*, "Control desacoplado de plataforma neumática de 3-GDL utilizada como simulador de movimiento," *Revista Iberoamericana de Automática e Informática Industrial*, vol. 8, pp. 345–356, 2011.

Iván Santana (S'10) received the B.S. degree in automatic control engineering and the M.S. degree in automatic engineering from the Universidad Central "Marta Abreu" de Las Villas (UCLV), Santa Clara, Cuba, in 1999 and 2004, respectively. Currently, he is working towards the Ph.D. degree in remote laboratories at the Universidad Politécnica de Madrid, Madrid, Spain.

He is currently an Assistant Professor with the Automatic and Computer Sciences Department and member of the GARP Research Group at UCLV. His main interests are remote laboratories, Web programming and intelligent control.

Manuel Ferre (M'04) received the Laurea degree in control engineering and electronics and the Ph.D. degree in automation and robotics from the Universidad Politécnica de Madrid (UPM), Madrid, Spain, in 1992 and 1997, respectively.

He is currently a Professor Titular at UPM. He has participated and coordinated several research projects in robotics and automatic control, both at national and international programs. His research interest is focused on automatic control, advanced telerobotics, and haptics. He has published over 100 papers in these fields, and also edited many publications, currently, is editor of the *Springer Series on Touch and Haptic Systems*. He is member of IEEE and

Prof. Ferre is a member of EuroHaptics Society. He serves as Chair of the RAS Technical Committee on Telerobotics.

Eduardo Izaguirre received the B.S. degree in automatic control engineering and the M.S. degree in automatic engineering from the Universidad Central "Marta Abreu" de Las Villas (UCLV), Santa Clara, Cuba, in 1985 in 1998, respectively.

He is currently an Assistant Professor with the Department of Automatic and Computer Sciences. He is a member of the GARP Research Group at UCLV. His current research interests include kinematics and dynamics modeling, simulation and control of industrial parallel robots.

Prof. Izaguirre received the Annual Innovation Award from the ANIR in 1993 and the National CITMA Award in 2007 from the National Academy of Sciences of Cuba.

Rafael Aracil (M'04) received the Degree in electrical engineering and the Ph.D. degree in control engineering from the Universidad Politecnica de Madrid, Madrid, Spain, in 1971 and 1975, respectively.

He is currently Director of the Centre for Automation and Robotics CAR UPM-CSIC, and Full Professor at UPM. Currently, he is working on the development of robots for news applications and intelligent teleoperation for different industrial enterprises. He is the author of several books, papers, and communications in the cited topics. He has worked in several European Union (EU)-funded projects such as ESPRIT, BRITE, and EUREKA. His main research interest is in the area of advanced manufacturing, robotics, and image processing.

Luis Hernández received the degree in automatic control and the Ph.D. degree in technical science from the Universidad Central "Marta Abreu" de Las Villas (UCLV), Santa Clara, Cuba, in 1981 and 1994, respectively.

He is the Project Leader of the Automation, Robotic and Perception Research Group (GARP) at the UCLV. His research interests are focused on automatic control, robotics, and autonomous vehicles. He is in charge of the University Collaboration Program between UCLV and the Council of Flemish Universities from Belgium.